

WHITE PAPER

An Analysis of Standard Temperature Rise Criteria for Ignition Safety of Combustibles

Ben Gaudet
Lead R&D Engineer
Fire Research and Development
UL Solutions

March 2024

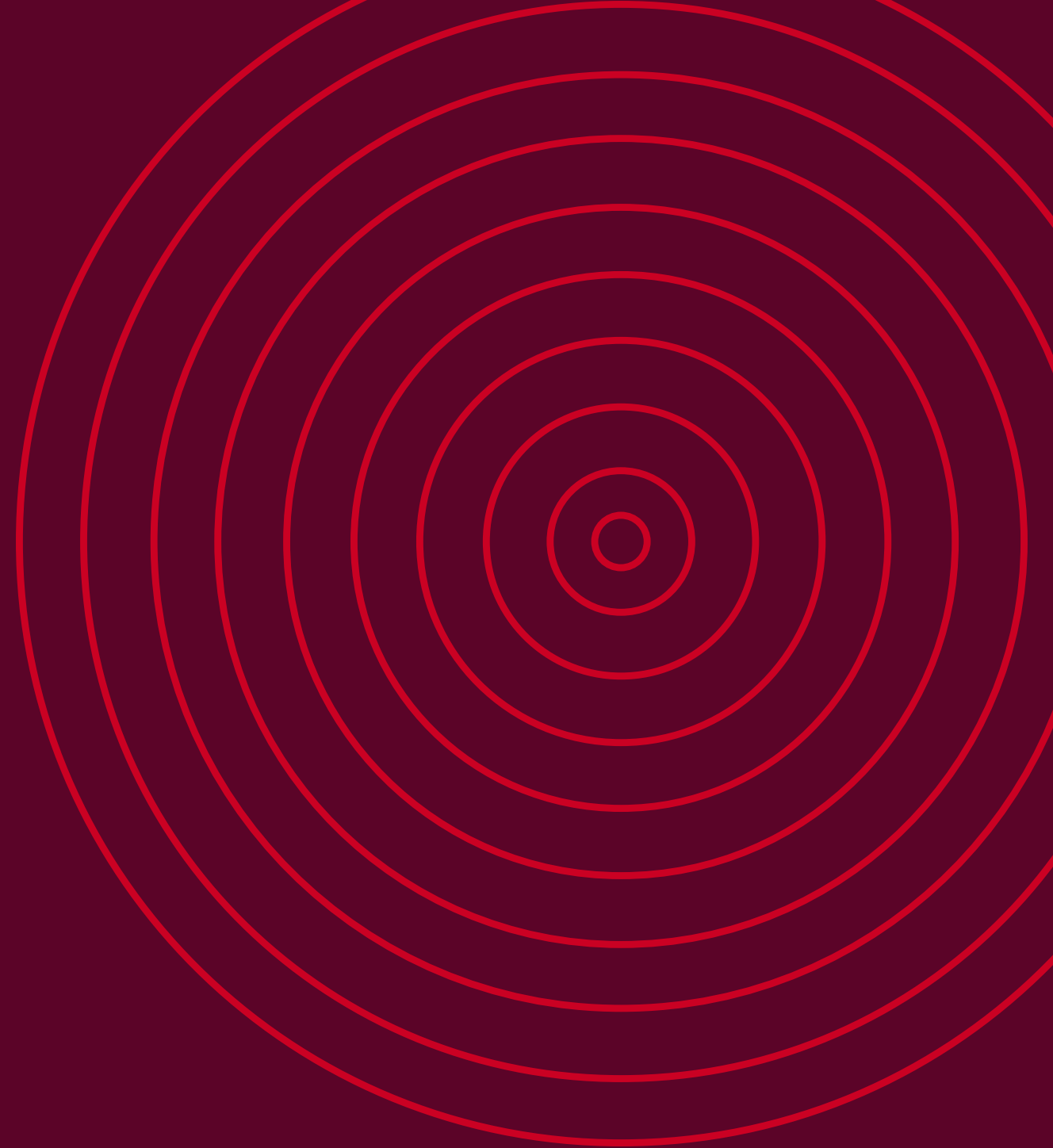
Table of contents

Abstract	4
Introduction	5
The temperature rise criteria in UL Standards	7
Thermal decomposition and ignition from short-term external heating	8
Ignition of wood from long-term heating	20
Fire investigations, incident reports and laboratory studies	20
Mechanisms of wood ignition from long-term vs. short-term heating	23
Comparison of thermal decomposition and ignition data with temperature rise criteria	26
Conclusions	28
References	29
Appendix A: Fire Investigation Images	33

THE CONTENT OF THIS DOCUMENT IS FOR GENERAL INFORMATION PURPOSES ONLY AND IS NOT INTENDED TO CONVEY LEGAL OR OTHER PROFESSIONAL ADVICE.

Abstract

Rise-above-ambient-temperature criteria are safety limits intended to mitigate hazards resulting from long- and short-term heat exposure from an appliance or device to its surroundings or its internals. This work explores the applicability of three temperature criteria — the 50°C, 65°C and 97°C rise-above-ambient-temperature criteria — to fire safety. The ranges of ignition temperatures and thermal decomposition temperatures of common combustible materials and historical fire investigation data were analyzed and compared to these criteria. Based on the data in this document, the 50°C and 65°C temperature rise criteria are applicable for mitigation of thermal decomposition and ignition risk when considering long-term heat exposure conditions. Similarly, the 97°C temperature rise criterion is applicable to short-term heat exposure conditions. No clear distinction exists for the use of the 50°C versus the 65°C temperature rise criteria for long-term ignition safety; however, the selection may be case-dependent.



Introduction

Common safety criteria related to thermal degradation and ignition hazards that are used in UL, CSA, EN, ISO, IEC and other certification standards are limits for the maximum temperature rise above ambient conditions that can result when a surface or object is exposed to a heat source. These criteria are found in several standards relevant to multiple industries and product types [1-20]. Primarily, they are found in standards applicable to heat-generating equipment, such as gas appliances, or products that may inadvertently cause heat fluxes that impinge on their surroundings due to fire or another malfunction.

The rise-above-ambient-temperature criteria are applied to components of the device under test or to materials and surfaces within proximity to the appliance or device. The purpose of these criteria is to prevent thermal degradation that may arise from heat exposure during both normal operation and select abnormal conditions. Abnormal conditions refer to unintended circumstances or the results of foreseeable misuses such as flow blockages, fan malfunction, temperature control device malfunction or fire. Thermal degradation leads to an increase in the risk of fire ignition, fire spread to a second item, electric shock, and product or system failure through the following mechanisms:

- Damage to corrosion protection, thermal insulation or electrical insulation
- Material creep, melting, distortion and sagging
- Pyrolysis

From an engineering standpoint, normal operating conditions may expose components or adjacent surfaces to long-term, relatively low heat fluxes. Conversely, abnormal conditions are expected to cause short-term, relatively higher heat fluxes. In this document, “long-term” refers to time periods that are days, months, years or otherwise indefinite. These lengths of time correspond to the expected operational life of a product.

“Short-term” refers to time periods of minutes or hours. During these time periods and conditions, the equipment cannot produce heat fluxes that cause thermal degradation to their surroundings. The rise-above-ambient-temperature criteria are intended to provide a limiting measurement during a standard test, beyond which the risk of thermal degradation is unacceptable. In a test setting, the criteria are usually applied to a wood-based material surface, e.g., plywood, that is constructed at a set distance from the boundary of the device under test.

Presently, three primary rise-above-ambient-temperature criteria — listed below — are observed in UL Standards published by UL Standards & Engagement (ULSE), as well as other certification standards. These temperature limits apply to surfaces in proximity to an appliance or device under test. While other criteria exist, this work focuses on the following temperature thresholds:

- 50°C (90°F) rise above ambient temperature
- 65°C (117°F) rise above ambient temperature
- 97°C (175°F) rise above ambient temperature

For the purposes of this document, “rise-above-ambient temperature criterion(a)” is shortened to “temperature rise criterion(a).”

The 50°C and 65°C temperature rise criteria both apply to normal operating conditions while the 97°C temperature rise criterion applies to abnormal conditions. The objective of this work is to explore the reported temperature ranges of thermal decomposition and ignition of common combustible materials, particularly wood and wood-based materials, and compare them to the 50°C, 65°C, and 97°C temperature rise criteria used in applicable ULSE end-product safety standards, i.e., UL Standards.

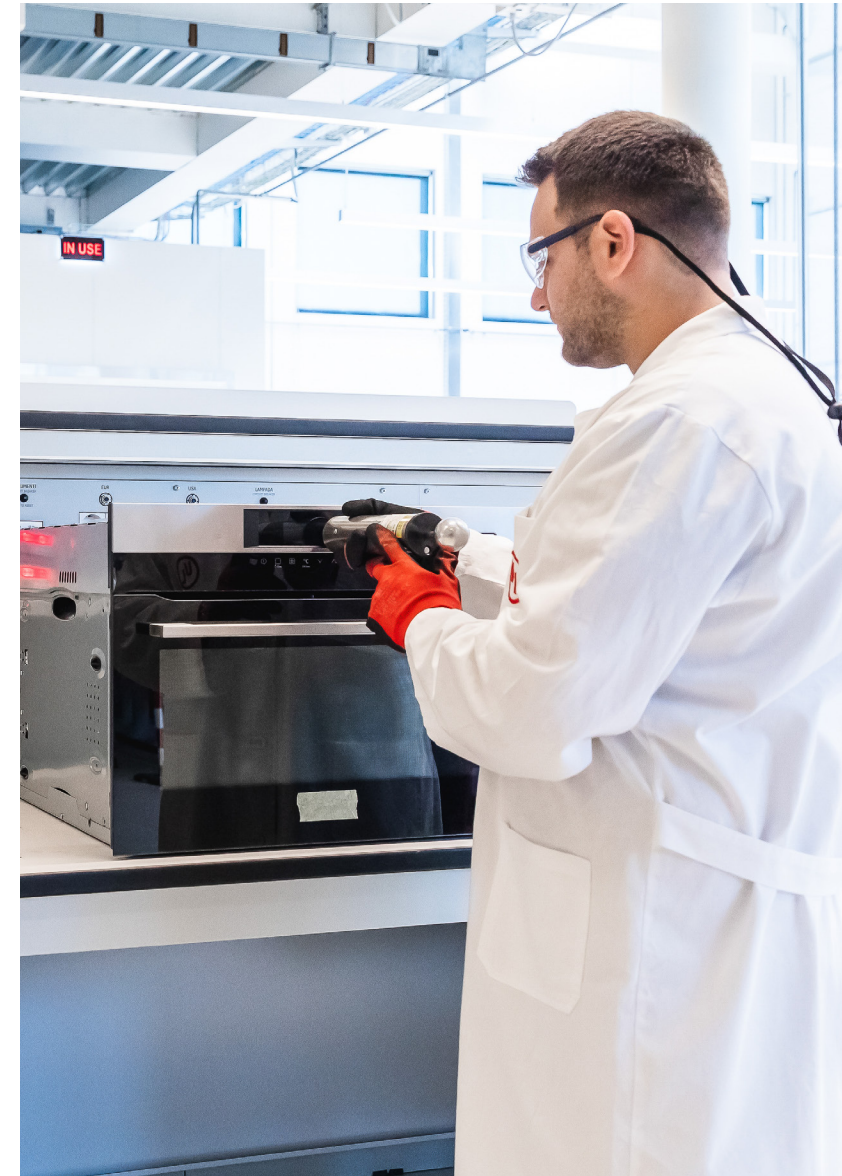
The temperature rise criteria in UL Standards

The 50°C temperature rise criterion (equivalent to a 90°F temperature rise criterion) can be traced back to an NFPA committee on gas-consuming appliances in 1919 [21]. The regulations promulgated by this committee included a clause that stated:

Gas-consuming appliances shall be arranged so that their continued operation will not raise the temperature of surrounding combustible material, including woodwork, more than 90°F from a normal temperature of 70°F: that is, a maximum of 160°F.

This criterion permeated out to other standard-development organizations including Underwriters Laboratories (UL). Two UL research bulletins released in 1943 and 1959 [22, 23], include reference to this criterion when determining safe minimum clearances between heat generating appliances, such as stoves and furnaces, and surrounding combustibles. The 97°C rise-over-ambient criterion has not been traced back to a single committee or standard. However, it is often found alongside the 50°C criterion in the performance requirements of several

UL Standards for wood-fired and oil-fired furnaces, stoves, heaters and fireplaces whose first editions were promulgated in the 1950s. For example, the 1955 first edition of UL 732, the Standard for Safety for Oil-Fired Water Heaters, lists the 50°C criterion for normal operation and the 97°C criterion during a burnoff test that simulates an abnormal firing condition [24]. The 65°C criterion is less common and also has not been traced to a single committee or standard. It is found in UL Standards first promulgated approximately 25 years later and applies to temperature rise from continuous operation. It has been used both in conjunction with, and instead of, the 50°C temperature rise criterion. For instance, a 1987 research review on wood heating safety lists the 65°C and 50°C temperature rise criteria for maximum temperature rise on exposed (visible) surfaces and unexposed (nonvisible or confined) surfaces, respectively [25]. The review cites the first edition of UL 1482, the Standard for Safety for Room Heaters, Solid Fuel Type, promulgated in 1979, as a source [26]. Conversely, UL 391, the Standard for Safety for Solid-fuel and Combination-Fuel Central and Supplementary Furnaces, uses the 65°C criterion instead of the 50°C criterion for temperature rise during continuous operation on all combustible test enclosure surfaces [27].



Thermal decomposition and ignition from short-term external heating

Thermal decomposition and ignition of a solid material from short-term external heating refers to a condition in which the external heat flux is high enough to cause ignition of a material. Heat transfer conditions at the material's surface result in a temperature increase that coincides with progressive thermal decomposition of the material (also called pyrolysis) and, eventually, ignition. The thermal decomposition consists of solid-phase chemical change and the production of flammable volatiles that can form a gaseous flammable mixture near the material's surface. Ignition of the material occurs when the flammable mixture begins to combust and flaming is sustained. Both ignition and thermal decomposition are strong functions of material properties such as chemical composition, density and specific heat capacity. They are also driven by the heat transfer conditions that cause temperature change of the material. Furthermore, ignition occurring at a solid material surface is affected by factors such as orientation, air currents, moisture, mixture ratio of thermal decomposition volatiles with air and the presence of a pilot energy source.

Ignition temperature

The lowest temperature at which a solid material will ignite and sustain combustion is sometimes referred to as the firepoint [28]. The temperature of the material surface at the firepoint is known as the ignition temperature (T_{ig}). T_{ig} is determined through one of a few standard test methods and is either measured directly or is inferred through a heat transfer model of the material sample. A parameter called the critical heat flux for ignition (CHF) is often measured and used in conjunction with a heat transfer model to calculate a value for T_{ig} . The CHF is the lowest external heat flux to cause ignition of a material under standard test conditions. In some cases, the ignition temperature is normalized with the thermal properties of the tested material in a value called the Thermal Response Parameter (TRP), given in Eq.1 [29, 30].

$$TRP = \sqrt{\left(\frac{\pi}{4} k \rho c_p\right)} (T_{ig} - T_o) \quad \text{Eq. 1}$$

Where k is thermal conductivity (W/m*K), ρ is density (kg/m³), c_p is specific heat capacity (kJ/kg*K), and T_o is the initial temperature. All parameters refer to the material sample.

In a standard testing condition, the TRP is also defined with the slope of a straight-line regression, m , fitted to a plot of the inverse of the square root of time to ignition, $\frac{1}{\sqrt{t_{ig}}}$, versus corresponding external incident heat flux, \dot{q}_e'' . This definition is expressed in Eq. 2.

$$TRP = \frac{1}{m} = \frac{\dot{q}_e''}{\frac{1}{\sqrt{t_{ig}}}} = \dot{q}_e'' \sqrt{t_{ig}} \quad \text{Eq. 2}$$

These parameters (CHF, T_{ig} , TRP) are part of engineering models of ignition phenomena called inert solid models that are a useful tool for fire safety design and analysis for ignition phenomena. The interested reader is directed to references [26, 27, 28] for a detailed explanation of these engineering models and the heat transfer assumptions used in them.

Standard test documents, as listed in Table 1 [31, 32, 33, 34], include methods for measuring or calculating CHF, T_{ig} and TRP. The standard test conditions are either conductive and convective heating by immersion of a material sample in a high-temperature oven or radiative heating by exposing the sample to a radiant heat source. In these methods, ignition is initiated by the presence of a pilot energy source, e.g. spark or pilot flame, that ignites the thermal decomposition volatiles evolving from the material sample as it heats. The piloted ignition approach improves test repeatability and typically results in lower, more conservative ignition temperature values compared to the case in which the hot sample is allowed to ignite on its own (auto-ignition).

Extensive tabulated data exist on critical heat fluxes, thermal response parameters and ignition temperatures of materials in engineering references [29, 30]. Excerpts of reported ignition temperatures and critical heat fluxes of select materials using measurements from the four standard methods in Table 1 — and variations of these methods — are given in Table 2 [28, 29, 30, 35]. The materials listed are common component materials in both construction and consumer products.

Table 1: Standard test methods for ignition by external heating

Standard	Measured quantities	Calculated quantity	Type of heating exposure
ASTM E 1321	CHF, t_{ig}	T_{ig}	Radiative heating
ASTM E 1354	CHF, t_{ig}	T_{ig}^*	Radiative heating
ASTM D 1929	T_{ig} , t_{ig}	N/A	Oven immersion
ASTM E 2058	CHF, t_{ig}	TRP	Radiative heating

T_{ig} may be calculated using the same method as presented in ASTM E1321, but this calculation is not explicitly given in ASTM E 1354.

Table 2: Reported data for piloted ignition temperature and critical heat flux for ignition

Material	Ignition temperature (°C)	Critical heat flux for ignition (kW/m ²)
Wood (various species)	250 – 497	7.5-15
Plywood	290 – 620	8.9-15.2
Oriented strand board (OSB)	348 – 365	14.3
Polyurethane foam*	272 – 490	13
Polymethyl methacrylate (PMMA)	195 – 383	6-23
Acrylonitrile butadiene styrene (ABS)	394 – 440	9-15
Rigid polyvinyl chloride (PVC)*	360 – 430	13-28
Low and high density polyethylene (LDPE / HDPE)	270 – 443	10-15
Cast Nylon 6	413 – 490	15-20
Polypropylene	250 – 443	10-15
Polyvinylidene fluoride (PVDF)	643	-

*Some reported values include formulations with fire retardants.

The tabulated Tig data provide temperature values where exposure to external heat fluxes at least as large as the corresponding values for CHF is expected to cause ignition in the short term. However, in many cases, 100°C-200°C of variation exists across datasets for different materials and for the same material. Also no inherent margin of safety exists in using tabulated ignition temperature values to develop ignition safety criteria. The temperature range of thermal decomposition provides an alternative benchmark for assessing ignition risk prior to the temperature range of ignition.



Thermal decomposition of plastics and wood-based materials — thermogravimetric analysis

Bench-scale testing using thermogravimetric analysis (TGA) was performed on a set of 13 materials to understand the range of temperatures that cause the onset of thermal decomposition in common combustible materials when exposed to external heating. Thermal decomposition causes evolution of gaseous volatiles from the material surface and, therefore, mass loss. TGA is a technique that subjects a material sample to immersion heating from a slowly heated crucible and measures mass loss with a load cell. The sample size and rate of temperature increase of the crucible are selected so the temperature of the crucible is assumed equivalent to the sample temperature.

Figure 1 plots TGA mass loss results for a set of common combustible materials used in construction and consumer products. The range of sample masses was within 2-9 mg. A single trial was performed with a crucible temperature ramp rate of 5°C per minute for each material. A lower heating rate was conservatively selected since onset temperature in TGA tends to increase with increased heating rate. Tests were conducted to maximum temperatures of 500°C-600°C. The crucible was flushed with nitrogen and testing was conducted in this nitrogen environment.

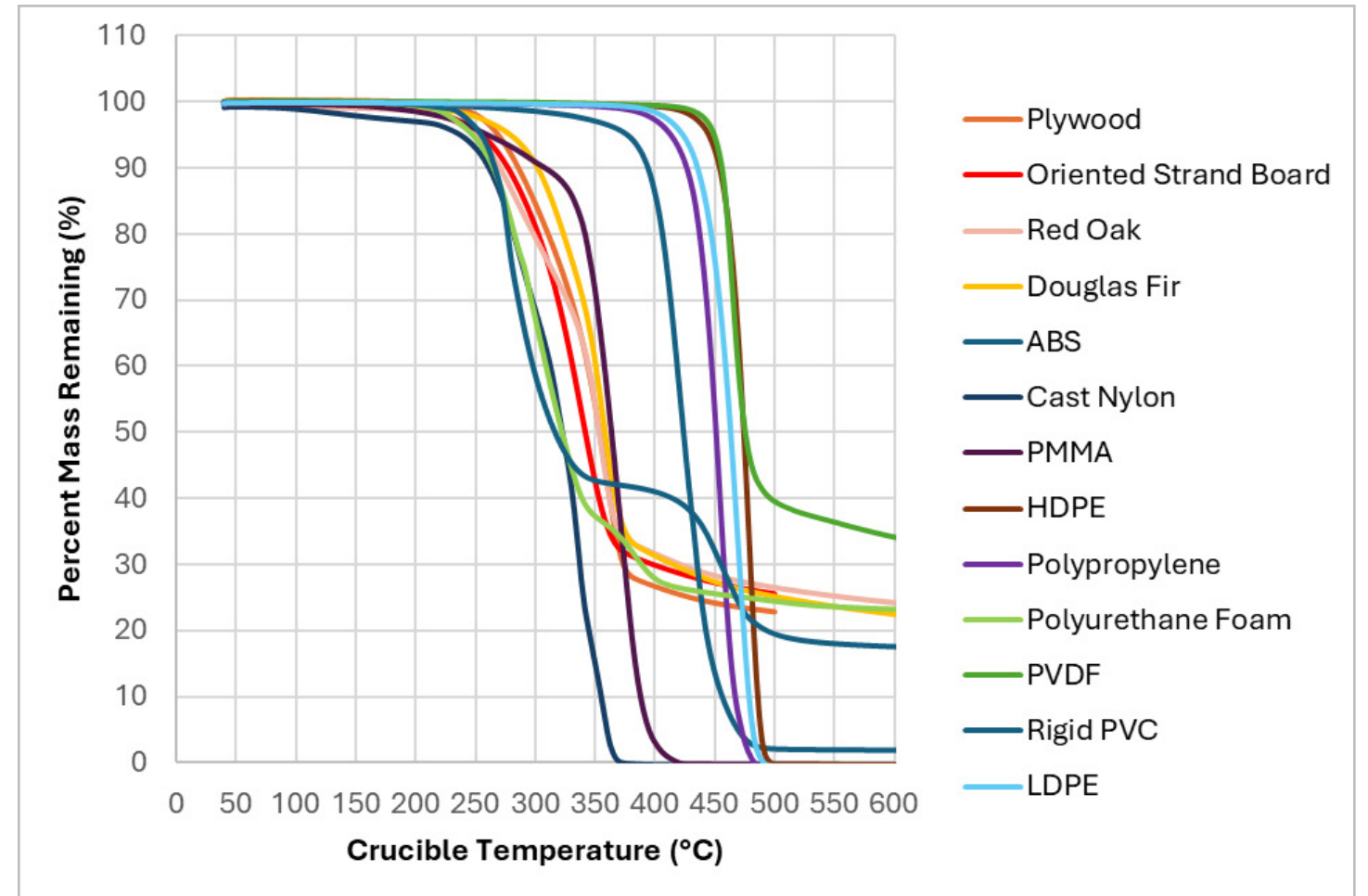
Table 3 lists the onset temperatures at which thermal decomposition begins for each material. ASTM E 2550 specifies onset in TGA as the point when “deflection is first observed from the established baseline prior to the thermal event” [36]. For purposes of quantification, this deflection is considered as the point at which 2% of initial mass is lost. It is assumed that mass loss is caused primarily by pyrolysis. In the case of wood-based materials (pure woods and wood products), this is also assumed for temperatures past 200°C [37]. The TGA data indicates a thermal decomposition onset temperature range of approximately 145°C-440°C for the tested materials.

Table 3: Thermogravimetric analysis onset temperature results

Material	Onset temperature (°C)	Material	Onset temperature (°C)
Plywood*	250	HDPE	431
Oriented strand board*	225	LDPE	406
Red oak*	220	Polypropylene	393
Douglas fir*	245	Polyurethane foam	227
PMMA	217	PVDF	440
ABS	328	Rigid PVC	240
Cast Nylon 6	145		

* Moisture content of the parent material of wood-based samples ranged from 6-10 %.

Figure 1: TGA results for thermal decomposition mass loss of common combustible materials



Thermal decomposition of wood-based materials — cone calorimeter testing

Additional bench scale testing was conducted on wood-based materials (Red oak, Douglas fir, oriented strand board, plywood) with an ASTM E 1354 cone calorimeter test apparatus. The test setup used custom exhaust gas sampling and sample surface temperature measurements to assess the generation of volatiles, prior to ignition, as a function of temperature under short-term radiant heat exposure. This testing was focused on wood-based materials because they (primarily plywood) are often used in UL Standards for combustible enclosures that surround a device under test [1-19]. Temperature rise criteria are applied to these wooden enclosures.

The cone calorimeter apparatus applies a radiative heat flux to a 100 mm x 100 mm x 12.4 mm thick sample using a conical heater placed above the sample and collects gaseous products of pyrolysis or combustion with an exhaust collection hood (Figure 3). Ignition is caused by a continuous pilot spark centrally located 25 mm above the sample. Constant radiative heat fluxes of 20 kW/m² and 35 kW/m² were applied to the samples. Three trials were conducted at each heat flux for each material (24 total tests). Tests were conducted up to and including ignition.

Gaseous products were captured through a collection hood and into an exhaust duct at a rate of 0.01 m³/s. For this study, the exhaust flow rate was intentionally reduced to this value from the ASTM E1354 standard rate of 0.024 m³/s to increase gas sample concentrations in the exhaust duct and thereby resolve smaller fluctuations in gas production.

During the thermal decomposition that precedes ignition, volume concentrations of two gases were measured in the exhaust stream: carbon monoxide (CO) and total hydrocarbons (THC). CO was measured because it is indicative of low-temperature, incomplete combustion that may be

present prior to flaming ignition. CO is also a standard gas measurement included in the ASTM E 1354 cone calorimetry instrumentation suite. THC is a measurement of unburnt hydrocarbon concentration in terms of a calibration hydrocarbon, i.e., propane. The hydrocarbon analyzer was calibrated to this gas prior to testing. This measurement provides a representative metric of flammable, complex pyrolyzate gases evolved from the heated sample prior to ignition.

THC is measured using flame ionization detection (FID). The measurement requires a heated line between the gas source and the analyzer to ensure hydrocarbon molecules do not condense out of the gaseous sample stream. CO concentration is measured with a non-dispersive infrared (NDIR) analyzer. The gas sampling locations are shown in Figure 2 and a diagram of the exhaust gas sampling system is shown in Figure 3.

Figure 2: Cone calorimeter diagram

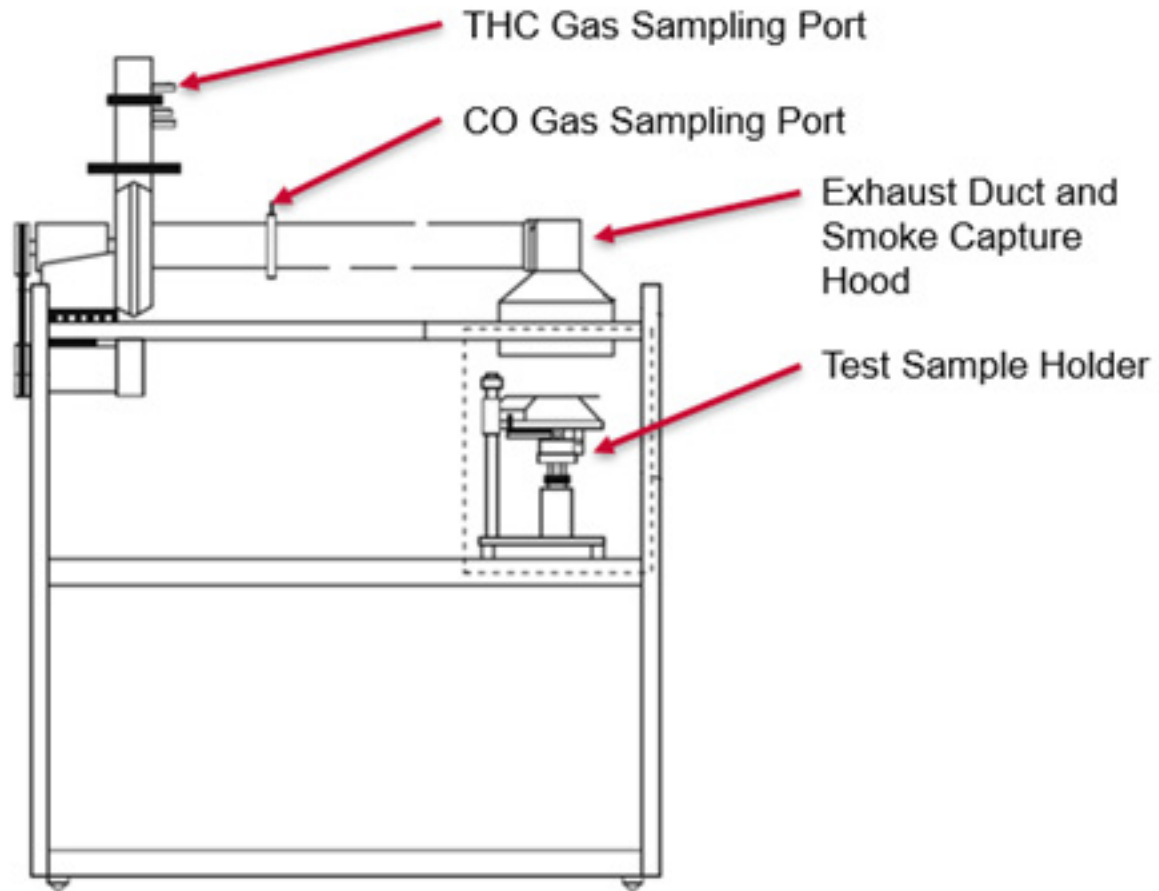
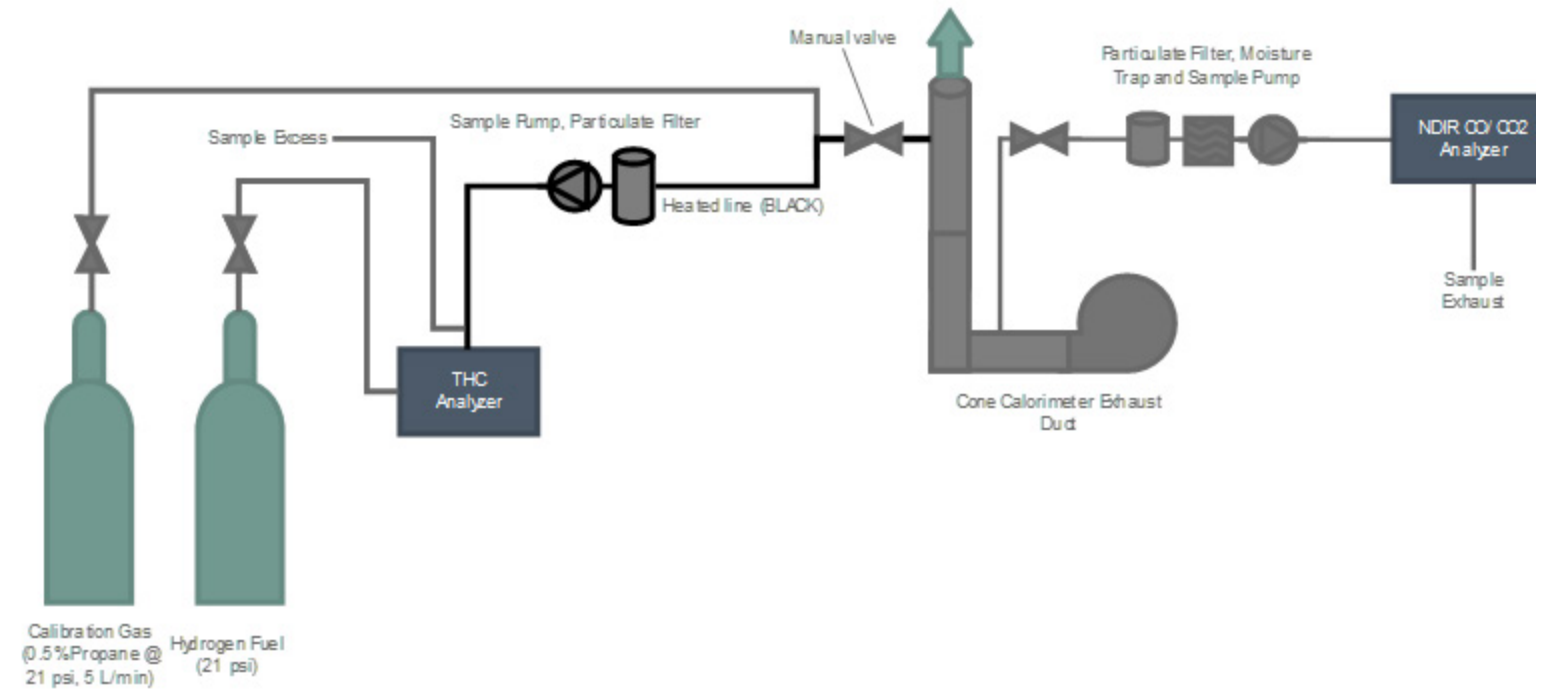


Figure 3: Exhaust gas sampling diagram



The surface temperature of the samples was measured with an exposed-junction, 30 AWG thermocouple centrally placed on the exposed surface of the sample. The thermocouple junction and leads were attached to a thin cantilever rod such that the thermocouple junction was held lightly against the sample surface by gravity, similar to a record needle. This setup is shown in Figure 4. A second exposed junction, 30 AWG thermocouple was installed on the unexposed side of each sample.

Figure 4: Cone calorimeter sample setup with surface temperature thermocouple measurement



Gas concentration measurements were plotted against exposed surface temperature measurements to indicate how the production of CO and THC changes with surface temperature up to the point of ignition. As an example, Figure 5 and Figure 6 show the surface temperature dataset for Douglas fir exposed to 20 kW/m² and 35 kW/m², respectively. The temperature spikes in the exposed surface temperature measurements on the right side of the plots are the points of ignition before the sample was extinguished.

Figure 5: Douglas fir surface temperature measurements at 20 kW/m² radiant heat exposure (No data for Trial 1 – unexposed surface)

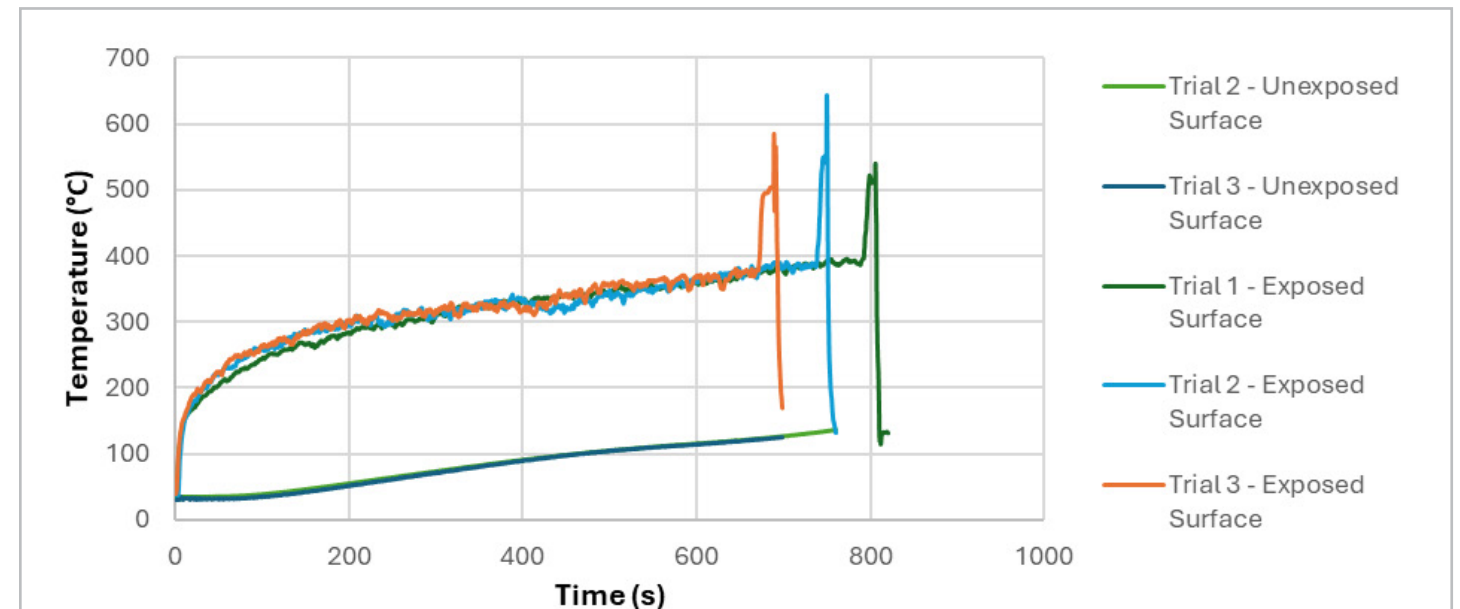


Figure 6: Douglas fir surface temperature measurements at 35 kW/m² radiant heat exposure

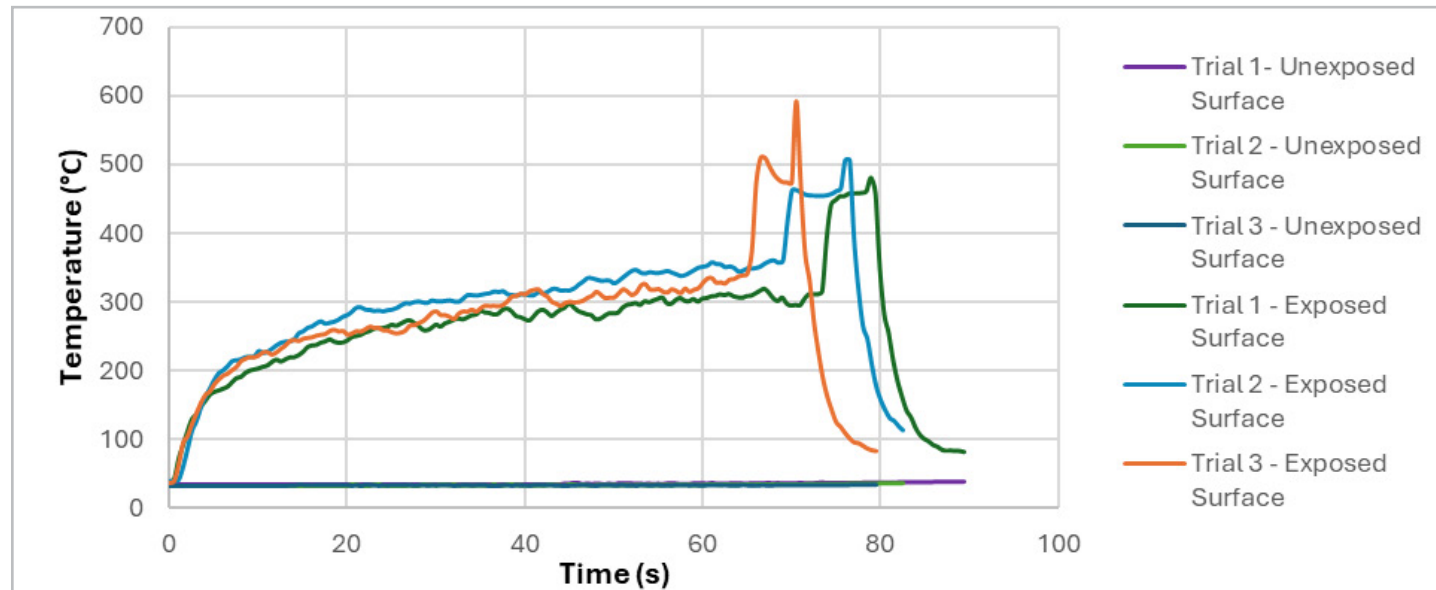


Figure 7 and Figure 8 plot CO and THC gas measurements against the exposed surface temperature measurements. The measured concentrations of THC are not exact concentrations of volatiles, but instead are relative concentrations in terms of propane equivalent. The data indicates positive inflection points where the production of CO and THC increase in response to increased temperature after a certain temperature range has been reached. The 20 kW/m² exposure resulted in increased heat diffusion into the samples prior to ignition, delayed ignition timing and increased production of volatiles before ignition than did the 35 kW/m² exposure.

Figure 9 is a compilation of data for all four wood-based material samples, at both heat flux setpoints, using the same format shown in Figure 7 and Figure 8. All data from each trial is plotted within a single color corresponding to the tested material. The corresponding plots of TGA mass loss for the same materials are also included. If the ranges of positive inflection in the production of THC and CO relative to surface temperature are considered the onset of thermal decomposition, then the onset temperature ranges align with those observed with TGA, as shown in Table 4.

Figure 7: CO production as a function of exposed surface temperature for Douglas fir

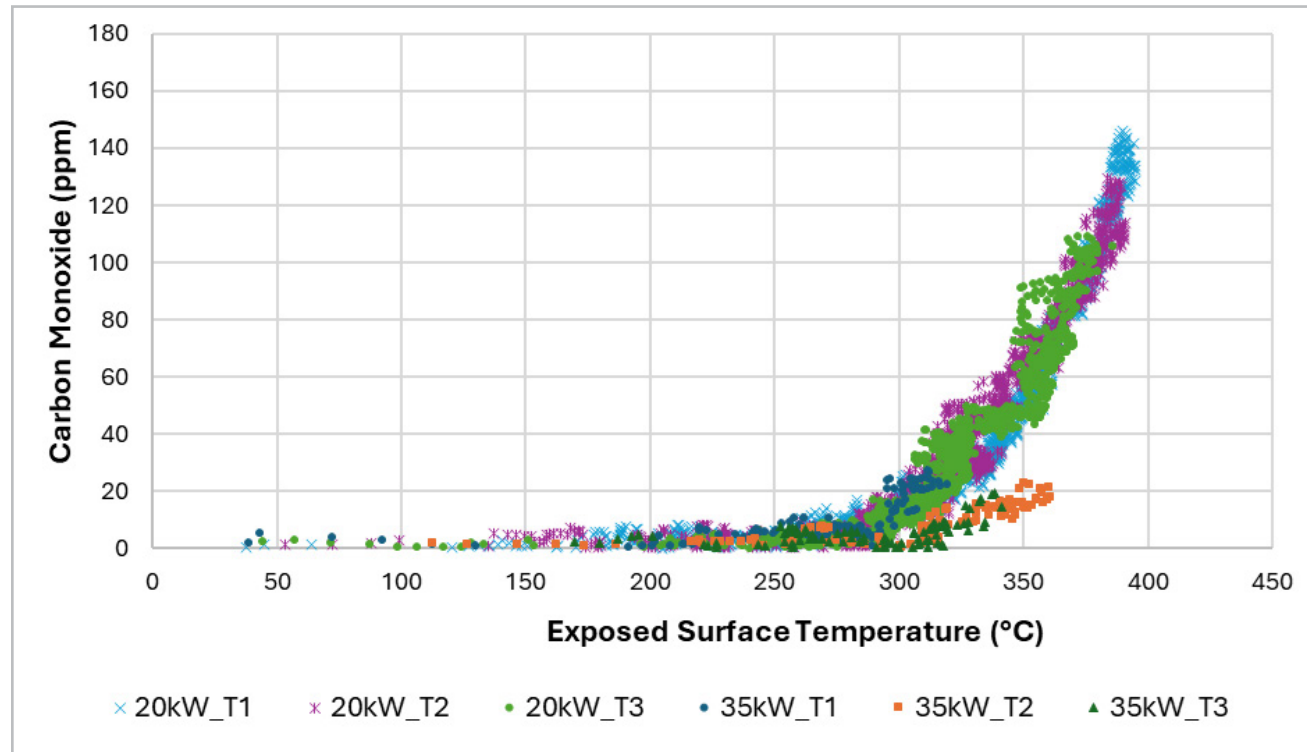


Figure 8: THC production as a function of exposed surface temperature for Douglas fir

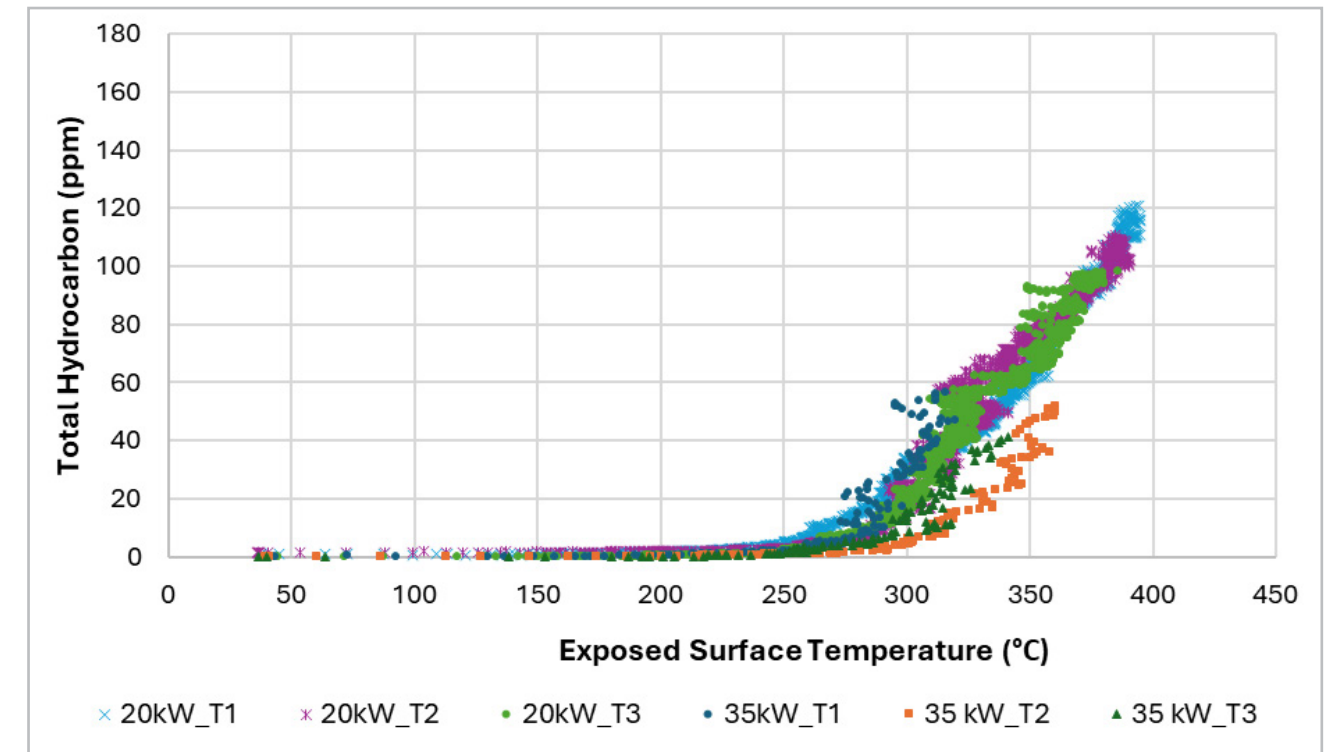


Figure 9: Comparison of TGA and cone calorimeter exhaust THC data for wood-based materials

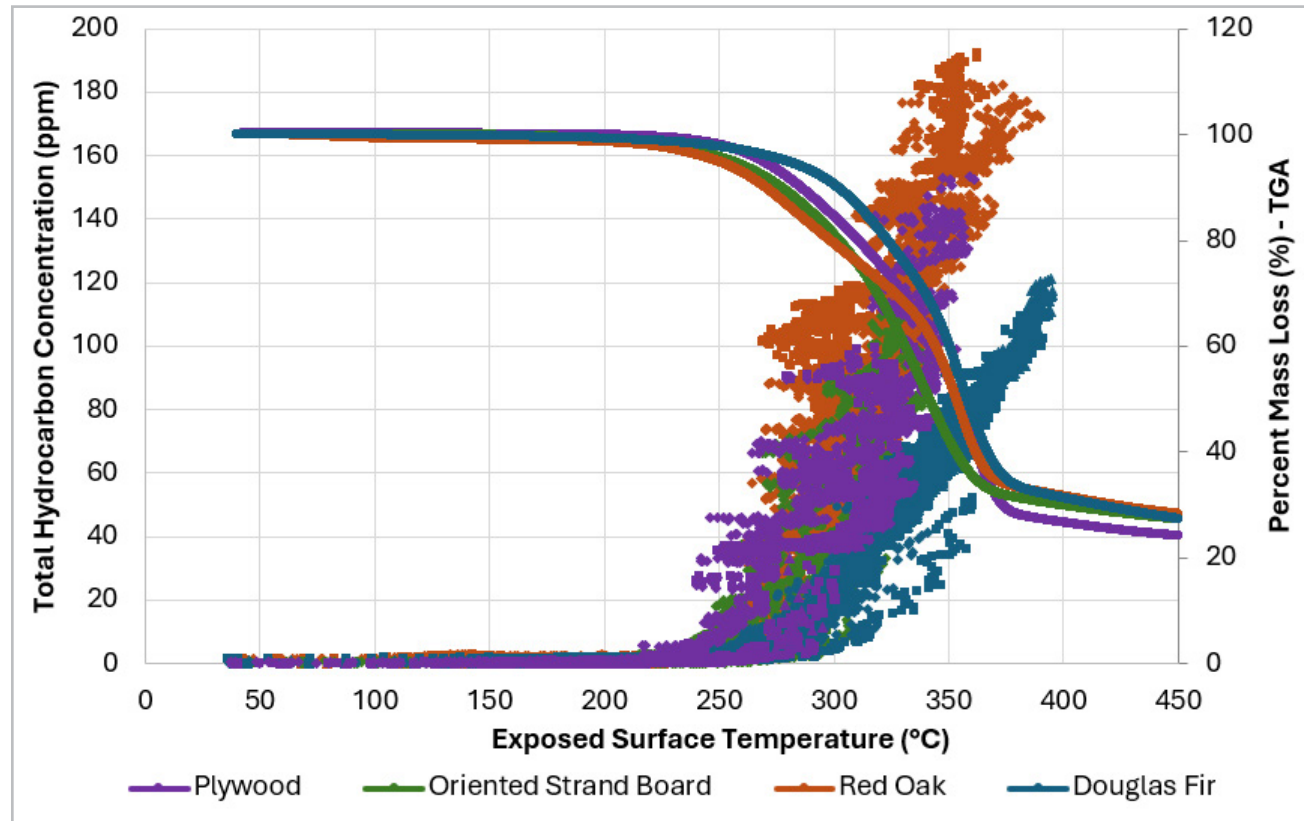


Figure 10: Comparison of TGA and cone calorimeter exhaust CO data for wood-based materials

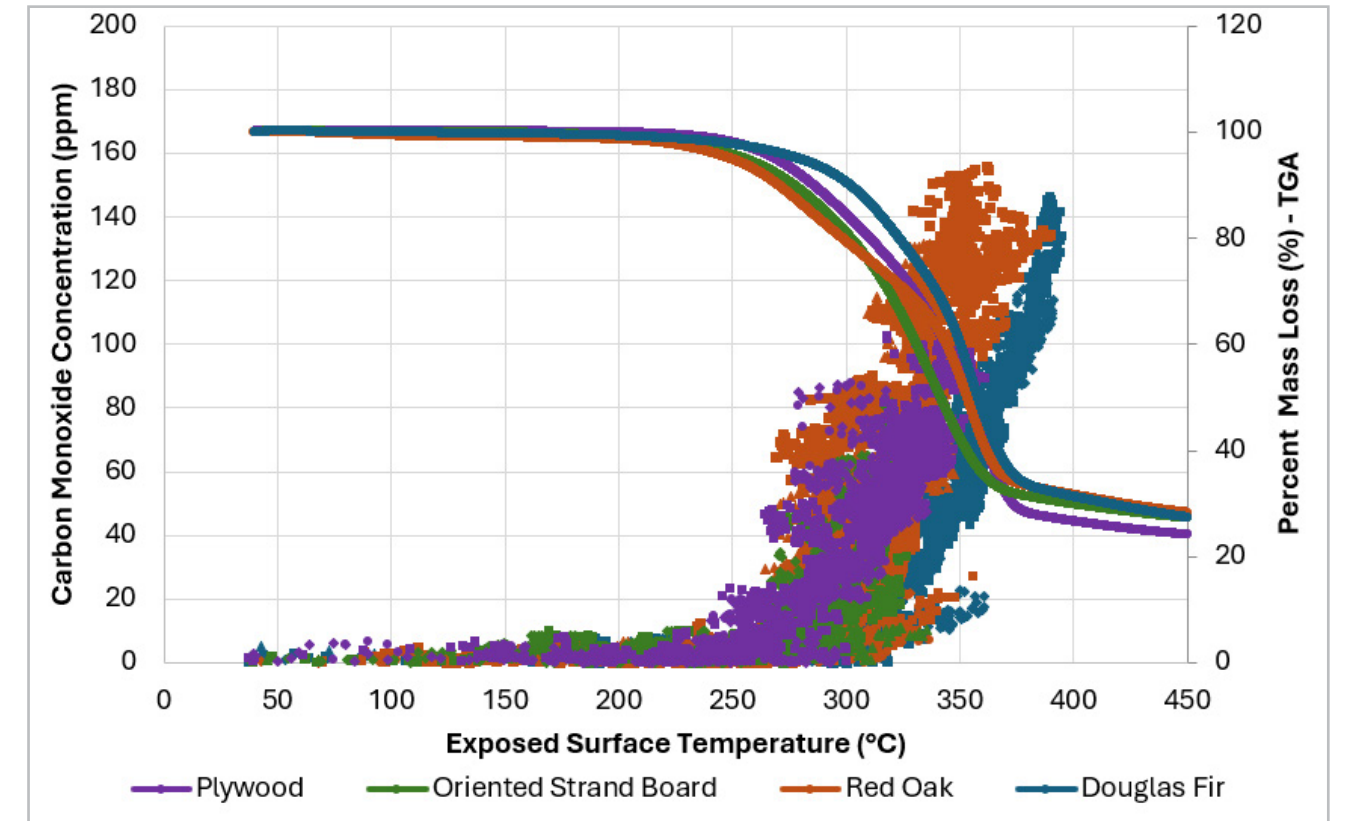


Table 4: Cone calorimeter testing results

Material	Onset temperature – TGA mass loss (TABLE 3)	Incident heat flux (kW/m ²)	Average onset temperature range – THC increase	Average onset temperature range – CO increase	Average measured ignition temperature	Average time to ignition
	(°C)		(°C)	(°C)	(°C)	(s)
Douglas fir	220	20	225 - 275	225 - 275	338	733
		35			305	70
Red oak	245	20	225 - 275	225 - 275	386	940
		35			350	76
Oriented strand board	225	20	225 - 275	225 - 275	330	245
		35			333	57
Plywood	250	20	225 - 275	225 - 275	338	530
		35			305	41

Instead of a specific onset temperature value, a 50°C onset temperature range is provided in Table 4 from the cone calorimeter test data. All four materials experienced onset of thermal decomposition, based on measured production of gaseous volatiles, between 225°C and 275°C. This temperatures range is reasonable given the 250°C lower limit of wood ignition temperature values observed in literature. Similarly, the wood and wood-based material samples experienced onset of mass loss during TGA at 220°C-250°C. Direct temperature measurements during cone calorimeter testing indicated ignition temperatures between 305°C and 350°C, which agree with tabulated literature ranges for wood, plywood and oriented strand board in Table 2.

*Some reported values include formulations with fire retardants.

Ignition of wood from long-term heating

In addition to ignition hazards from heat fluxes that ignite combustible materials in the short-term, evidence exists of another ignition phenomenon of wood and wood-based materials that has been historically investigated at the same time as the implementation of the temperature rise criteria in UL Standards. This phenomenon — referred to as long term, low temperature ignition — is based on observational evidence from fire investigations and incident reports of wooden materials catching fire after long-term exposure to temperatures and heat fluxes below the range that causes ignition during short-term external heat exposure, i.e., tabulated ignition temperatures. Records of these fire events have been found back to the late 1800s and into the 2000s.

Fire investigations, incident reports and laboratory studies

In the late 1800s and early 1900s, several instances were recorded of fires appearing to have originated from low-pressure steam pipes and similar hot objects installed in contact with wooden structural members. An article published in NFPA Quarterly in 1911 included a list of 50 accounts collected by the Independence Inspection Bureau of fires originating from low-pressure and high-pressure steam pipes in contact with flammable material in various industrial settings [38]. In most cases, the flammable material was wooden members or sawdust. In 1918 and 1921, two separate NFPA articles were published discussing two long-term ignition events in detail [39,40]. The first article discussed an instance of wooden members becoming charred after prolonged exposure to a steam coil. The second article describes a fire that originated within a floor assembly through which an uninsulated low-pressure steam pipe was passing to reach “an ordinary office radiator.” In 1925, a second compilation report of an additional 15 steam-pipe related fire events was published in NFPA Quarterly [41]. The article opens with the statement “that wood can ignite at comparatively low temperatures when they are of long duration, has long been a well established fact.”

In the following years, Underwriters Laboratories Inc (UL) became involved in investigation of similar events. In 1940, UL investigated two separate fires in Chicago that occurred in the same storage shed [42]. The shed was constructed of wood against the brick/concrete wall of an adjacent building. Among other things, the shed contained a 125 hp boiler in close contact with the brick wall that had been in operation for 15 years. The fires occurred in the wooden floor beneath the boiler where the floor contacted the wall. Investigation of the fires involved measurement of temperatures on the shed walls, where steady-state temperatures of 88 °C were measured. It was postulated that in the floor assembly where the fires occurred, temperatures as high as 100 °C may have occurred due to better insulating properties and underventilation. Seventeen years later, during a UL field survey for heat-generating equipment in 1957, “15 [additional] incidents of fires alleged to have been started by low-pressure steam or hot-water pipes in contact with wood were encountered” [23].

Outside of the United States, the same fire problem was being observed. During a visit to Stockholm, Sweden, a UL

representative was presented with a report of a fire originating from a hot water storage tank installed in contact with a softwood wall for a period of several years. In this instance, the maximum possible temperature of the tank was 100°C [23]. An additional 14 instances involving steam pipes, hot water tanks, boilers and hot air ducts were recorded from Sweden and Finland, five of which involved temperature of 100°C or less and thirteen of which involved temperatures under 120°C. Many of these incidents were included in a 1960 report by the Swedish Fire Protection Association [43]. Among them, one incident involved a dry-kiln exhaust duct igniting the wood-shaving filling that surrounded the duct. The supposed maximum temperature of the duct was 65°C [43, 23]. No timeframe of exposure was specified. This case-study involves the lowest recorded temperature for a long-term ignition event of a wood-based material that has been found in the present work.

It is possible that multiple instances reported in the NFPA Quarterly articles and elsewhere involve steam pipes at pressures higher than atmospheric pressure, therefore resulting in steam temperatures above 100°C. Steam pipes at pressures much higher than atmospheric are common, especially when considering industrial applications. Because the temperature of a steam pipe is a function of its operating

pressure, low-pressure pipes operating at 30 psi or lower can contain steam at a temperature up to 120°C [44]. Industrial pipes at a pressure of 125 psig can reach over 175°C. However, multiple accounts, such as those reported from Sweden and Finland, involved vessels and pipes containing liquid water under atmospheric pressure. In these cases, the temperature of the pipes and vessels cannot physically reach above 100°C under their own heat generation. Additionally, the majority of recorded steam-pipe incidents involve low-pressure steam, indicating temperatures of 120°C or lower.

Scenarios involving ignition of wood related to long-term heat exposure have been reported into the 21st century. These incidents involved hot-water pipes, steampipes, and other heat-generating equipment. One account that is illustrated in multiple literature reviews of long term, low-temperature ignition of wood involves a hot-water pipe running through a floor/ceiling assembly in a family home [30, 44, 46]. The pipe was reported as operating at 77°C prior to the fire and was in bare contact with the floor/ceiling assembly components. An image of the fire origin is given in Figure A1 of Appendix A. In 2001, another report surfaced in Winnipeg, Canada, of an uninsulated hot-water pipe operating at 88°C–93°C that caused ignition in a wooden wall partition that the pipe was passing through

[45]. Apart from water and steam pipes, a series of three fires occurred between 1997 and 2003 involving heat-generating kitchen equipment installed in the three separate locations of the same restaurant chain (See Appendix A, Figures A2 and A3) [46]. In all three cases, fires originated in the wall cavity behind a cheese-melter that was wall-mounted with steel screws. Analysis of other chain locations where fires had not yet occurred showed charring around the mounting screws that supported the cheese-melter assemblies. Recreations of the fire scene in the laboratory, using the same kitchen equipment as is used in the restaurants, showed that average temperatures near 120°C could be produced within the wall assembly due to cyclical heating representative of the kitchen schedule. The investigation concluded that ignition may be caused by exposure to these temperatures in the wall assemblies when cyclically heated for a matter of “approximately 21 months.”

Early laboratory studies to understand the propensity of wood to ignite at relatively low temperatures after long-term exposure were being conducted throughout the first half of the 1900s. Most early studies involved plunging wood samples (usually blocks or wedges of various shapes and sizes) into heated environments at specified temperatures for specified periods of time. In 1944, the Forest Product Laboratory of the U.S.

Forest Service conducted a series of tests exposing matchstick-sized wooden wedges to temperatures of 107°C-150°C for continuous time periods of 165-1,050 days [48]. Specimens exposed to 150°C for 165 days were completely transformed to charcoal while specimens exposed to 107°C for 1,050 days presented a “light chocolate color,” indicating the presence of charring. While no ignition occurred, the author stated that the results “are no guarantee that [the samples] could not have [ignited] if conditions more favorable to combustion had prevailed.” Similar testing in 1951 observed charring but no ignition in wood samples when exposed to heating conditions between 93°C and 177°C for several months [49].

Other testing has been conducted which focused specifically on the phenomenon of steam-pipe ignition of wood-based materials. In 1910, a series of laboratory tests were conducted in which steam pipes were installed in direct contact with pine blocks and sawdust [50]. Test specimens were contained within compartments built around the pipe. In the case of the pine blocks, the pipes were installed through holes bored into the samples. The pipe was pressurized to an average of 125 psi and temperatures ranging from 138°C-167°C were measured in the compartments containing the test specimens. Heating was applied 10 hours a day for 67 days. Variations in air supply were also provided. Following testing, both the

sawdust and pine blocks charred substantially. A ¼” char layer was observed in the pine blocks around the pipe surface. However, no ignition was observed. In Canada, a similar test was conducted by the National Research Council Canada (NRCC) to reproduce steam pipe ignitions in the laboratory [51]. Few details are given in the account of the experiments other than that a heat exposure of approximately 120°C was applied to a wood sample built around a steam pipe for a continuous application of 4 years. Charring, but no ignition, was observed.

Fire incidents and investigations spanning a century have reported thermal degradation, charring and fires originating from wood that was exposed to temperatures in the range of 65°C to 120°C for long-term time periods. The early laboratory investigations, while never directly replicating the phenomenon of ignition, observed charring in wood samples exposed to temperatures ranging from approximately 100°C to 170°C after long-term time heat exposure.



Mechanisms of wood ignition from long-term vs. short-term heating

Although observational evidence exists of long-term, low-temperature ignition of wood, this phenomenon is less understood than ignition from short-term heat exposure. Over a century of empirical data is available for ignition temperatures of wood and other combustible materials involving heat exposures severe enough to cause ignition in a matter of minutes or up to 1-3 hours, i.e., the short term. Several engineering models also exist for predicting ignition in these conditions based on heat transfer and chemical kinetics. For a given combustible material, variables such as test apparatus, heat exposure mode, heat exposure time, temperature measurement method, sample size, sample orientation, sample moisture content, sample chemical treatment and sample species has led to both a large volume and large range of data for ignition temperatures and thermal decomposition parameters under short-term heat exposure.

When considering a wood specimen that is exposed to an external heat flux and is thermally decomposing, four decomposition regimes have been identified [37]:

- **REGIME 1 (100°C-200°C):** Wood dehydrates and “initial decomposition” begins
- **REGIME 2 (200°C-300°C):** Wood components “begin to undergo significant pyrolysis” and

thermal degradation. Low-temperature pathways of pyrolysis are initiated. Production of carbon monoxide (CO) and hydrocarbons occurs. At this temperature range, smoldering can be initiated at the interface between the material and ambient air.

- **REGIME 3 (300°C - 450°C):** “Vigorous production of flammable volatile” occurs and high-temperature pathways of pyrolysis are initiated.
- **REGIME 4 (450°C -):** Most residue is “non-volatizing char” that further degrades and oxidizes.

Most wood ignition temperature data for short-term exposure results in ignition temperatures within Regime 3 (Table 2 and Table 4) [28, 29, 30, 35]. Available data suggests that the lower limit for ignition of wood due to short-term heat exposure is within Regime 2. The mechanism of ignition identified during short-term heating experiments is a critical mass flux of volatiles being produced by a condensed-phase surface and a sufficient energy source being present to ignite the combustible volatile-air mixture above the surface [28, 29]. The energy source could be a pilot, e.g., spark or flame, or the hot surface itself (auto-ignition). In the case of wood, at temperatures beneath those required for the critical mass flux of volatiles needed for flaming

ignition, smoldering ignition can occur. In this mode of ignition, wood material that has been decomposed to char begins to oxidize rapidly in a self-sustaining manner but without flaming.

For long-term ignition of wood, one or a combination of two mechanisms have been cited:

1. Internal self-heating
2. The formation of pyrophoric char

These mechanisms, respectively, would cause ignition of wood at lower temperatures than is observed for short-term external heat exposure by:

1. Creating a self-heating thermal runaway condition within the wood material due to exothermic reactions until temperatures within Regimes 2 or 3 are produced, combined with the availability of oxygen, and ignition occurs (usually smoldering ignition followed by transition to flaming).
2. Decomposing the wood material into another chemical form that has a reduced ignition temperature and therefore different decomposition regimes.

Self-heating is based on the internal heat generation of a reactive substance exceeding its ability to lose the heat generated. The reactivity of the substance, the exothermicity of the chemical reaction involved, moisture content, the ambient temperature surrounding the material and the dimensions of the material bulk all play a role in the magnitude of self-heating [28, 52, 53]. This phenomenon is usually observed in large piles of porous materials that are heated by oxidative or microbially induced exothermic reactions from the inside out. Ignition of wood-chip piles and large blocks of fiberboard are examples of self-heating ignition (also called spontaneous ignition) [53, 54]. In extreme cases, ambient temperatures near room temperature can lead to ignition in certain materials via self-heating. For engineering purposes, the Frank-Kamenetskii (F-K) model is a mathematical model used to predict the critical ambient temperatures and material dimensions for self-heating ignition of a bulk of material.

The F-K theory has been used to model the self-heating propensity of wood chips and solid wood blocks to examine long-term wood ignition incidents [55]. From laboratory experiments that subjected wood blocks of varying sizes to ambient temperature of varying levels, predictions were made of the critical dimensions and ambient temperature needed to ignite solid wood from self-heating. The results argue that

either larger dimensions or higher ambient temperatures are required for self-heating thermal runaway of solid wood blocks than is reported in forensic fire investigations of long-term, low-temperature ignition of wood. Critics of this view have pointed out that the long-term exposure timeframe over which the studies are conducted (a matter of days or weeks) are not applicable to the long-term timeframes seen in actual reported fire events (months or years) [45]. In addition, it is argued that the assumptions and simplifications involved both in the testing and applying of the F-K theory may not apply to the complex self-heating phenomena involved in long-term ignition of wood members in a real-world scenario [45].

Pyrophoric char or pyrophoric carbon is a term originating in 1902 that was developed to explain the phenomenon of ignition at low temperatures (including self-heating ignition of porous materials such as haystacks). The idea was that virgin wood or cellulosic material, after being sufficiently heated, would convert to a carbonaceous char material that was “more readily ignitable” [45]. The concept of pyrophoric char suggests that the decomposition pathway to ignition would change after the transition to char and, therefore, ignition temperature would change as well. Experiments assessing this concept were performed with plywood samples subjected to varying levels of heating pre-treatment and then tested using a cone calorimeter,

TGA and differential scanning calorimetry (DSC) [56]. Level of pre-treatment was determined by the percent of original sample weight that remained after pre-treatment. It was found that pretreating (charring) the wood had no effect on the minimum heat flux required for ignition. Pre-treated samples also did not show different thermal decomposition trends compared to virgin wood samples during TGA or DSC testing. Instead, the pretreated wood samples were further along the same decomposition trend observed for virgin wood samples. The experiments suggested that wood char contained no separate or pyrophoric properties compared to virgin wood. However, while providing insight into the decomposition pathways of wood, the timeframes involved with the testing were eight hours or less, which is less exposure time than is observed for field incidents of long term, low-temperature ignition of wood.

Literature indicates that char does not have separate pyrophoric properties relative to virgin wood. Other work has explored the ability of char to improve the propensity of wood materials to self-heat and ignite. As wood decomposes and forms char, the surfaces of solid wood begin to crack, fissure and shrink away. This process increases porosity and allows oxygen to diffuse deeper into the wood, providing a physical means of increasing propensity for ignition. The importance of oxygen diffusion on self-heating ignition of solid

wood has been exemplified by burn patterns developed on 20 cm blocks of wood that were ignited through self-heating after one day in an atmosphere of 200°C [55]. The hourglass burn pattern that resulted from testing showed substantially greater charring from the end-grain sides of the block. The patterns correspond to the greater porosity of wood from an end-grain direction than from a cross-grain direction.

The presence of oxygen when char is being formed has been shown to change the reactivity of the char and, therefore, the propensity for self-heating and ignition. Initial work on this topic showed that chars formed in anaerobic atmospheres (no oxygen) were more reactive when exposed to air than chars formed in aerobic atmospheres [57]. The reactivity refers to a process called chemisorption of oxygen. This is the process of absorption and bonding of a molecule into a surface. In other words, anaerobic chars have a higher inclination to absorb ambient oxygen and produce exothermic oxidation reactions than do aerobic chars. Further work showed that both types of char do not display different thermal decomposition pathways, similar to how aerobic char and virgin wood do not show different pathways [58, 59]. However, the work also supported the idea that anaerobic chars are more prone to absorbing ambient oxygen and supporting oxidation than are aerobic chars. Other findings included the trend that

heating chars in anaerobic conditions for longer periods of time increased reactivity when finally exposed to ambient air.

Literature review indicates that no complete theory is currently available to explain or predict long-term, low-temperature ignition of wood. Additionally, no experiments conducted in controlled laboratory conditions have been found that successfully caused ignition in wood specimens at temperatures between 65°C and 120°C — the temperature range observed in fire investigations and incident reports. However, no experiments have been found which simultaneously mimic the timeframe, heating conditions and installation conditions of a reported ignition event in a single test.

What studies have shown is that:

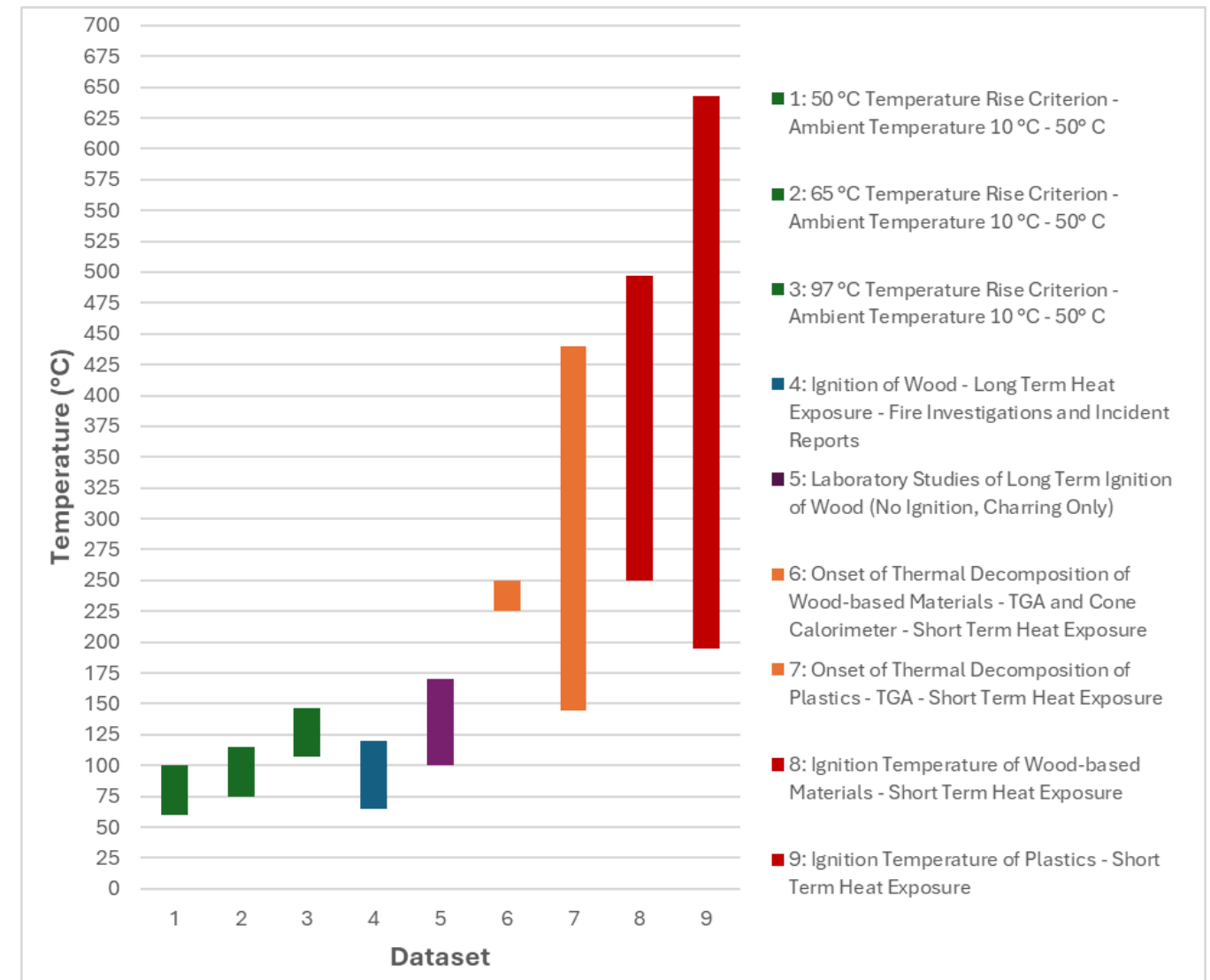
- Self-heating does occur within solid wood and can lead to ignition from initial exposure temperatures lower than tabulated ignition temperatures.
- Charring increases the propensity for ignition by improving oxygen diffusion into the solid wood.
- Char formed in normal conditions is highly reactive with ambient oxygen, yet char formed in oxygen-restricted conditions is more reactive.

Some references have insisted that the correct sequence of events related to heating conditions and char formation could explain long-term, low-temperature ignition fire incidents [45, 46, 58]. For example, long-term heating of a wooden member in air-restricted, well-insulated conditions can result in highly reactive anaerobic char. Upon continued fissuring, cracking, and long-term degradation of the char and the structural assembly, improved oxygen diffusion is allowed, increased exothermic oxidation reactions occur and thermal runaway begins, leading to ignition. A sequence like this resembles multiple reported long-term, low-temperature ignition events, which occurred in confined spaces such as wall cavities and floor assemblies adjacent to heat generating equipment.

Comparison of thermal decomposition and ignition data with temperature rise criteria

Literature data and the work presented here provide temperature ranges at which thermal decomposition and ignition of a variety of combustible materials are observed after short-term external heating. A lower temperature range also exists at which observational data suggests hazards develop for wood ignition in which a more complicated interaction of mechanisms including internal self-heating and thermal insulation, char formation and availability of oxygen play roles. Figure 11 compares reported temperature ranges for ignition and thermal decomposition from short-term external heating, long-term ignition scenarios of wood, long-term wood charring laboratory studies, and the 50°C, 65°C and 97°C temperature rise criteria. A range of temperatures is provided for the temperature rise criteria assuming ambient temperature variation between 10°C and 50°C.

Figure 11: Summary of temperature range datasets



The 50°C and 65°C temperature rise criteria fall in a similar range as observed temperatures of long-term ignition of wood and overlap the lower end of the temperature ranges used for laboratory work that observed substantial wood charring after long-term heat exposure. This correlation can be viewed in context of the historical timeframe when this ignition hazard was being observed and when the temperature rise criteria were proposed and accepted in UL Standards or were otherwise promulgated. While the mechanisms that lead to ignition were and are still not fully understood, observational evidence exists to support the risk of fire occurring from wood-based materials being exposed to temperatures within the range of 65°C to 120°C for long-term time periods. These risks were becoming apparent and reports of supporting incidents were emerging throughout the 20th century at the same time UL Standards for heat generating equipment were being developed, promulgated and updated.

Researchers not engaged in standard development have also suggested temperature criteria to combat the risk of long-term, low-temperature ignition of wood. Some authors propose a maximum absolute temperature of 100°C [51, 60]. This value aligns with the beginning of Regime 1 of the

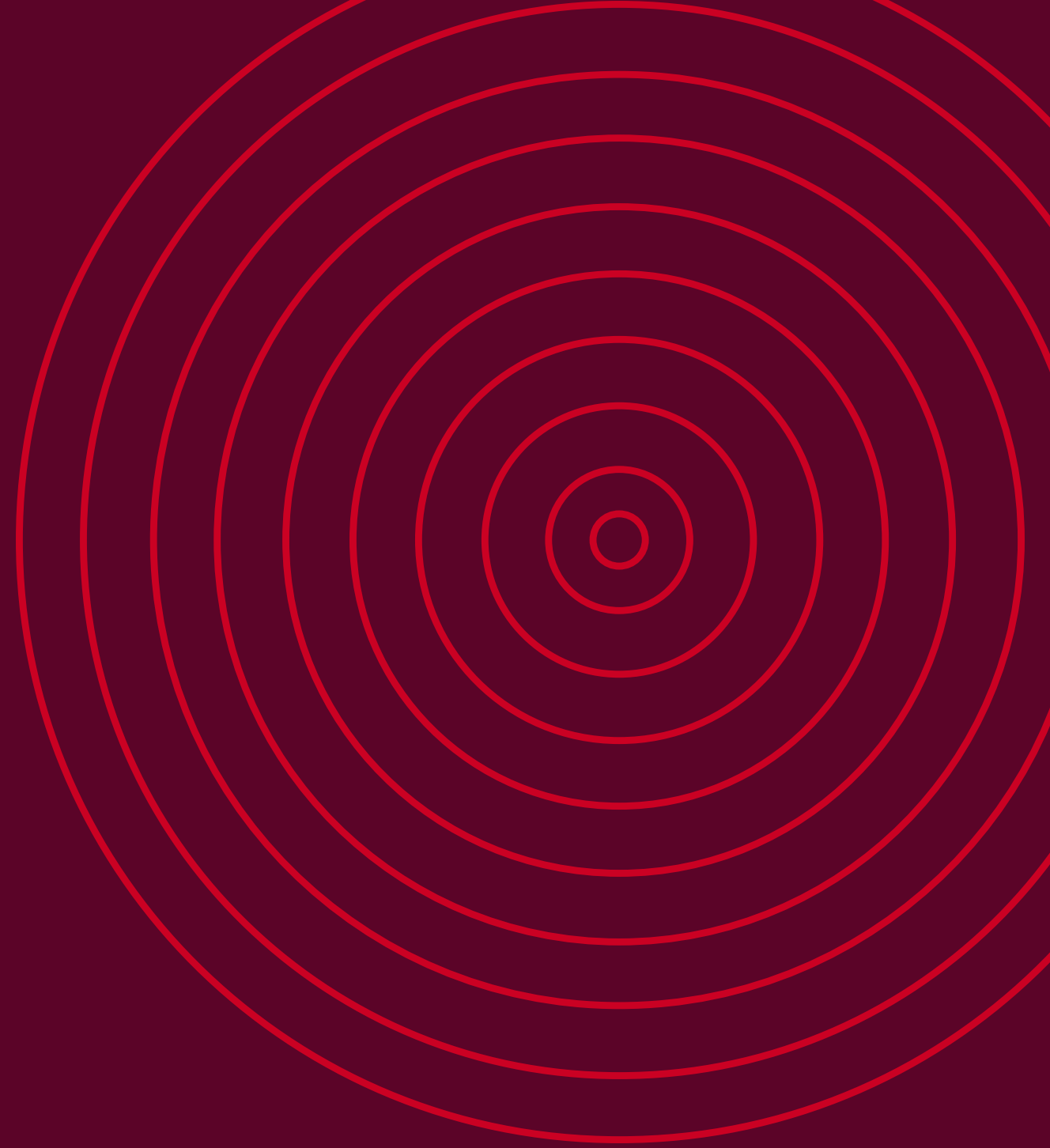
decomposition of wood. 100°C also aligns with the average of the incident report and fire investigation data referenced in the present work when excluding high-pressure steam pipes. Others have proposed an absolute temperature of 77°C based on the single lowest recorded temperature of ignition of solid wood (not including wood shavings) [46].

While both the 50°C and 65°C temperature-rise criteria apply to conditions of indefinite heat exposure, in some UL Standards, the 65°C criterion is applied to exposed surfaces while the 50°C criterion is applied to unexposed surfaces. Unexposed surfaces could include “beneath the appliance, floor protector or wall-mounted protective device” [25]. The former criterion is a 30% margin above the latter. This allocation of criteria reflects both consideration of an observer being able to notice thermal degradation of an exposed surface as well as the tendency of long-term ignition events to occur in unexposed, confined areas. In these environments, the variables that have been shown to increase propensity for self-heating of wood, i.e. creation of anaerobic char, char cracking, and fissuring, thermal insulation, are all more likely.

The 97°C temperature rise criterion resides below the reported data for temperatures of thermal decomposition and ignition for the selected plastics and wood-based materials from short-term heat exposure. The upper limit of the 97°C criterion closely coincides with the lower limit of the TGA data for plastics, lies within Regime 1 of wood decomposition and is approximately 50°C-100°C below literature values for ignition temperature. With this placement, it provides a margin of varying magnitude before ignition risk arises from short-term heat exposure. This agrees with its use in safety standards for abnormal, short-term conditions. However, it resides mostly above the range of temperatures reported for long-term ignition of wood and so may not be applicable to continuous, normal operation conditions in safety standards.

Conclusions

Based on the data in this document, the 50°C and 65°C temperature rise criteria are applicable for mitigation of thermal decomposition and ignition risk when considering long-term heat exposure conditions. Similarly, the 97°C temperature rise criterion is applicable to short-term heat exposure conditions. The 50°C and 65°C temperature rise criteria both overlap the observed range of ignition risk of wood from long term heating, and both precede or minorly overlap the temperature ranges of wood charring data from long-term laboratory studies. For these reasons, no clear distinction exists between the use of one criterion over the other when applied to long-term ignition safety. However, the use case plays a role in determining which criterion to apply. Factors such as creep, sagging and melting of a material, e.g., electrical insulation, or structural weakening of a material, e.g., reduced strength of wood [37], become relevant when considering long-term exposure to elevated temperatures. Consideration of these factors and the anticipated range of ambient temperatures help determine whether the 50°C or the 65°C temperature rise criteria is most applicable for safety.



References

1. Underwriters Laboratories Inc. (2010). UL 103, Standard for Safety for Factory-Built Chimneys for Residential Type and Building Heating Appliances, 11th Ed.
2. Underwriters Laboratories Inc. (2011). UL 127, Standard for Safety for Factory-Built Fireplaces, 10th Ed.
3. Underwriters Laboratories Inc (2010). UL 391, Standard for Safety for Solid-Fuel and Combination-Fuel Central and Supplementary Furnaces, 5th Ed.
4. Underwriters Laboratories Inc. (2018). UL 727, Standard for Safety for Oil-Fired Central Furnaces, 10th ed.
5. Underwriters Laboratories Inc. (2003). UL 729, Standard for Safety for Oil-Fired Floor Furnaces, 6th ed.
6. Underwriters Laboratories Inc. (2003). UL 730, Standard for Safety for Oil-Fired Wall Furnaces, 5th ed.
7. Underwriters Laboratories Inc. (2018). UL 731, Standard for Safety for Oil-Fired Unit Heaters, 6th ed.
8. Underwriters Laboratories Inc. (2023). UL 732, Standard for Safety for Oil-Fired Storage Tank Water Heaters, 7th ed.
9. Underwriters Laboratories Inc. (2019). UL 733, Standard for Safety for Oil-Fired Air Heaters and Direct-Fired Heaters, 5th ed.
10. Underwriters Laboratories Inc. (1993). UL 647, Standard for Safety for Unvented Kerosene-Fire Room Heaters and Portable Heaters, 2nd ed.
11. Underwriters Laboratories Inc. (2016). UL 795, Standard for Safety for Commercial-Industrial Gas Heating Equipment, 8th ed.
12. Underwriters Laboratories Inc. (1993). UL 896, Standard for Safety for Oil-Burning Stoves, 5th ed.
13. Underwriters Laboratories Inc. (2011). UL 1482, Standard for Safety for Solid Fuel Room Heaters, 7th ed.
14. Underwriters Laboratories Inc. (2010). UL 1978, Standard for Safety for Grease Ducts, 4th ed.
15. Underwriters Laboratories Inc. (2015). UL 1995, Standard for Safety for Heating and Cooling Equipment, 5th ed.
16. Underwriters Laboratories Inc. (2006). UL 2096, Standard for Safety for Commercial/Industrial Gas and/or Oil-Burning Assemblies with Emission Reduction Equipment, 3rd ed.
17. Underwriters Laboratories Inc. (2016). UL 2561, Standard for Safety for 1400 Degree Fahrenheit Factory-Built Chimneys, 2nd ed.
18. Underwriters Laboratories Inc. (2010). UL 2790, Standard for Safety for Commercial Incinerators, 1st ed.

References

19. Underwriters Laboratories Inc. (2019). UL 8782, Outline of Investigation for Pollution Control Units for Commercial Cooking Operations
20. Underwriters Laboratories Inc. (2019). UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems, 3rd ed.
21. National Fire Protection Association (1919). Proceedings of Twenty-Third Annual Meeting, pg. 228.
22. Neale, John A. (1943). Bulletin of Research No.27, "Clearances and Insulation of Heating Appliances". Underwriters Laboratories Inc.
23. Matson, A.F; Dufour, R.E.; Breen, J.F. (1959). Bulletin of Research No.51, Part II: "Survey of Available Information on Ignition of Wood Exposed to Moderately Elevated Temperatures". Underwriters Laboratories Inc.
24. Underwriters Laboratories Inc. (1955). UL 732, Standard for Safety for Oil-Fires Water Heaters, 1st ed.
25. Peacock, R. D. (1987). Wood heating safety research: an update. *Fire technology*, 23(4), 292-312.
26. Underwriters Laboratories. (1981). UL 391, Standard for Safety for Solid-fuel and Combination-fuel Central and Supplementary Furnaces, 1st ed.
27. Underwriters Laboratories. (1979). UL 1482, Standard for Safety for Room Heaters, Solid Fuel Type, 1st ed.
28. Drysdale, Dougal. (2011). *An Introduction to Fire Dynamics*, 3rd ed. Chapter 6: Ignition: The Initiation of Flaming Combustion. John Wiley & Sons Ltd. West Sussex, UK.
29. Hurley, M. J., Gottuk, D. T., Hall Jr, J. R., Harada, K., Kuligowski, E. D., Puchovsky, M., ... & WIECZOREK, C. J. (Eds.). (2015). *SFPE handbook of fire protection engineering*. Springer.
30. Babrauskas, V. (2003). *Ignition handbook* (Vol. 318). Chapter 7: Common Solids. Fire science publishers: Issaquah, WA
31. ASTM International (2022). ASTM E1321 – 22: Standard Test Method for Determining Material Ignition and Flame Spread Properties.
32. ASTM International (2018). ASTM E1354 – 18: Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter.
33. ASTM International (2019). ASTM E2058 – 19: Standard Test Methods for Measurement of Material Flammability Using a Fire Propagation Apparatus (FPA).
34. ASTM International (2013). ASTM D1929 – 20: Standard Test Methods for Determining Ignition Temperature of Plastics.
35. Babrauskas, V. (2002). Ignition of wood: a review of the state of the art. *Journal of Fire Protection Engineering*, 12(3), 163-189.

References

36. ASTM International (2021). ASTM E2550 – 21: Standard Test Method for Thermal Stability by Thermogravimetry.
37. Dietenberger, M., & Hasburgh, L. (2016). Wood products thermal degradation and fire. Reference module in materials science and materials engineering, 1-8.
38. Independence Inspection Bureau (1911). “Fire Dangers of Steam Pipes”. Quarterly of the National Fire Protection Association, Vol. 4, Issue 3, pg. 312-322.
39. “Charring of Wooden Supports by Steam Coil” (1918), Quarterly of the National Fire Protection Association, Vol.12, pg. 28.
40. Drugan, H.E. (1921). “Another Steam Pipe Fire”. Quarterly of the National Fire Protection Association. Vol. 14, pg. 290.
41. Whorf (1925). “Low Temperature Ignition of Wood”. Quarterly of the National Fire Protection Association. Vol. 19, Issue 2, pg. 157-167
42. Underwriters Laboratories Inc (1940). Data Card, C60, Serial No UL198. “Wood, Ignition of at Low Temperatures”.
43. Ostlin, B. (1960). [Translated] “Ignition of Wood at Temperatures below the Normal Ignition Point”., Svenska Papperstidning, pg. 225-227.
44. Yunus, A. C. (2010). Fluid Mechanics: Fundamentals And Applications Tata McGraw Hill Education.
45. Babrauskas, V. (2001). ‘Pyrophoric Carbon’ and Long-term, Low-temperature Ignition of Wood. Fire and Arson Investigator, 51(2).
46. Babrauskas, V., Gray, B. F., & Janssens, M. L. (2007). Prudent practices for the design and installation of heat-producing devices near wood materials. Fire and Materials: An International Journal, 31(2), 125-135.
47. Warren, J. H; Tindal, J.R. (2004). The Warren Group, Inc. “Forensic Engineering Analysis of Low Temperature Ignition of Wood”.
48. McNaughton, G.C. (1944). “Ignition and Charring Temperatures of Wood”. R1464, U.S. Forest Products Laboratory.
49. MacLean, J.D. (1951). “Rate of Disintegration of Wood Under Different Heating Conditions”. American Wood-Preservers Association.
50. Bixel, E.C.; Moore, H.J. (1910). “Are Fires Caused by Steam Pipes?”, Thesis, Case School of Applied Science.
51. McGuire, J. H. (1969). Limiting safe surface temperature of combustible materials. Fire Technology, 5(3), 237-241.
52. Zalosh, R. G. (2003). Industrial fire protection engineering (pp. 266-268). Hoboken, NJ: Wiley.
53. Gray, B.F.; Sexton, M.J.; Halliburton, B.; Macaskill, C. (2002). Wetting induced ignition of cellulosic materials. Fire Safety. Pg. 465-479.

References

54. Mehaffey, J. R., Richardson, L. R., Batista, M., & Gueorguiev, S. (2000). Self-heating and spontaneous ignition of fibreboard insulating panels. *Fire technology*, 36(4), 226-235.
55. Cuzzillo, B. R., & Pagni, P. J. (2000). The myth of pyrophoric carbon. *Fire Safety Science*, 6, 301-312.
56. Swann, J. H., Hartman, J. R., & Beyler, C. L. (2008). Study of radiant smoldering ignition of plywood subjected to prolonged heating using the cone calorimeter, TGA, and DSC. *Fire Safety Science*, 9, 155-166.
57. Bradbury, A. G. W., & Shafizadeh, F. (1980). Role of oxygen chemisorption in low-temperature ignition of cellulose. *Combust. Flame;(United States)*, 37.
58. AN, Hoang. N. Q. (2009). Pyrolysis and propensity to self-ignition of long-term low-temperature wood chars (Doctoral dissertation).
59. Lim, S. M., & Chew, M. Y. L. (2007). Chemisorption And Low-Temperature Pyrolysis Of Wood Chars In Smoldering Combustion. *Fire Safety Science*, 7, 127-127.
60. Schaffer, E. L. (1980). Smoldering initiation in cellulose under prolonged low-level heating. *Fire Technology*, 16(1), 22-28.

Appendix A: Fire Investigation Images

Figure A1: Fire origin traced back to hot-water pipes in bare-contact with a floor assembly [46]



This image is from a commonly cited case of a fire originating from long-term, low-temperature heat exposure in 1972. The investigation concluded that the temperature of the hot-water pipe was 77°C. Long-term cyclical heat exposure from the pipe to the enclosed floor assembly eventually caused a fire within the assembly. Clear charring is visible where the fire spread within the floor assembly and up along the pipe insulation. The pipe insulation was neglected in the space where the pipes passed through the floor.

Figure A2: Heating pattern on back of ‘cheese-melter’ and corresponding burn pattern inside the wall assembly [47]



During investigation of the first of three restaurant fires, a high-heat pattern was found on the backside of the cheese-melter (left photo). Within the wall assembly where the cheese-melter was installed, a corresponding pattern is found (right photo). These patterns indicated that a fire originated within the wall cavity directly behind the right side of the cheese-melter and spread radially within the wall assembly before being extinguished. Laboratory testing that recreated the fire scene found that temperatures of approximately 120°C can be produced at the interface of the equipment and the wood blocking on the wall that supported the cheese-melter.

Figure A3: Charring occurring around a screw mount after long-term installation of an industrial ‘cheese-melter’ [47]



Following multiple fires in the same restaurant chain, investigators surveyed other locations of the same chain to observe any damage that may be present. Charring was found in the wooden mounting blocks surrounding the mounting screws, indicating heat transfer from the cheese-melter into the wall assembly.



[UL.com/Solutions](https://www.ul.com/solutions)